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# Dark Radiation and Inflationary Freedom

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We perform a cosmological analysis in which we allow the primordial power spectrum of scalar perturbations to assume a shape that is different with respect to the usual power-law, arising from the simplest models of cosmological inflation. We parametrize the primordial power spectrum with a piecewise monotone cubic Hermite function and we use it to investigate how the constraints on the various cosmological parameters change: we find that the obtained limits are relaxed with respect to the power-law case, if CMB polarization data are not included. Moreover, the cosmological analyses provide us some indications about the shape of the reconstructed primordial power spectrum, where we notice possible features around  $k \simeq 0.002 \text{ Mpc}^{-1}$  and  $k \simeq 0.0035 \text{ Mpc}^{-1}$ . If confirmed in future analyses involving enhanced experimental data, these features suggests that the simplest cosmological inflation models may be incomplete.

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# 1 Introduction

In the cosmological analyses, one of the main assumptions about the early Universe is the power-law form of the Primordial Power Spectrum (PPS), that is predicted by the simplest models of inflation. Deviations from the simplest inflationary models can in principle lead to different shapes of the PPS with respect to the power-law form. Any cosmological analysis performed assuming a power-law PPS, in turn, can give biased constraints on the cosmological parameters.

We study how the freedom in the PPS shape can affect the limits on the cosmological parameters, with particular interest on the bounds on the presence in the early Universe of additional dark radiation. Among the main candidates, the most studied in the literature are axions (not treated here, see Ref. [1]) or neutrinos.

## 2 Method

We base our analysis on a flat  $\Lambda$ CDM model, described by the usual parameters: the present-day physical CDM and baryon densities  $\Omega_{\text{cdm}}h^2$  and  $\Omega_{\text{b}}h^2$ , the angular sound horizon  $\theta_s$ , the optical depth to reionization  $\tau$ .

We will study two properties of dark radiation, considering the cases of three massive neutrinos or of additional massless neutrinos. To accommodate the presence of dark radiation, we extend then the  $\Lambda$ CDM model varying the sum of the neutrino masses  $\Sigma m_\nu$  or the effective number of relativistic degrees of freedom  $N_{\text{eff}}$ , respectively.

When we consider the standard *power-law* (PL) PPS, we describe it using the usual parameters  $n_s$  and  $\ln(10^{10}A_s)$ , respectively its spectral index and its amplitude.

Following [2], we parametrize the *free* PPS of scalar perturbations with a “piece-wise cubic Hermite interpolating polynomial” or PCHIP. We use  $N = 12$  nodes to be interpolated with the PCHIP function: ten equally spaced nodes in the range ( $k_2 = 0.001 \text{ Mpc}^{-1}$ ,  $k_{11} = 0.35 \text{ Mpc}^{-1}$ ), better constrained from the data, and two nodes  $k_1 = 5 \cdot 10^{-6} \text{ Mpc}^{-1}$  and  $k_{12} = 10 \text{ Mpc}^{-1}$ , necessary to parametrize a non-constant behavior at the outermost wavemodes. The spectrum is described by  $P_s(k) = P_0 \times \text{PCHIP}(k, P_{s,j})$ , where  $P_0 = 2.2 \cdot 10^{-9}$  is an arbitrary normalization,  $P_{s,j} = P_s(k_j)/P_0$  and  $0.01 \leq P_{s,j} \leq 10$ .

For our analyses, we consider the following experimental data sets: full CMB temperature plus polarization data at low multipoles only (Planck TT+lowP) or full temperature and polarization data (Planck TT,TE,EE+lowP) from the Planck 2015 release [3], and the data on the matter power spectrum at different redshifts from the WiggleZ Dark Energy Survey (MPkW) [4].

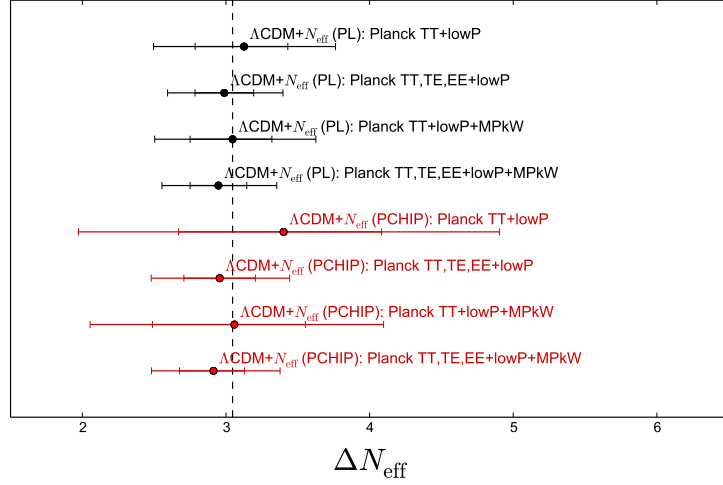


Figure 1: Limits on  $N_{\text{eff}}$  at 1, 2  $\sigma$ . Adapted from Ref. [1].

### 3 Results on $N_{\text{eff}}$ and $\Sigma m_\nu$

The strongest degeneracies between the PCHIP nodes and a cosmological parameter appear for the effective number of relativistic species,  $N_{\text{eff}}$ . A comparison of the  $N_{\text{eff}}$  constraints obtained using the power-law and the PCHIP PPS is reported in Fig. 1.

The reason of the strong degeneracy is related to the effects of varying  $N_{\text{eff}}$  in cosmology. When  $N_{\text{eff}}$  is increased with fixed matter-radiation equality and matter-dark energy equality redshifts, the Silk damping at small scales is enhanced (see e.g. [5]). If one modifies the scalar PPS, increasing it only at the scales interested by the enhanced Silk damping and not at the other scales, the effects of a larger  $N_{\text{eff}}$  can be canceled. This is the reason for which the model with the free PPS, considering Planck TT+lowP data only, allows high values of  $N_{\text{eff}}$ : the PPS freedom allows to modify the small scales without altering the large scales, so that a large  $N_{\text{eff}}$  can be accommodated. As expected, the degeneracies between  $N_{\text{eff}}$  and the nodes  $P_{s,j}$  are stronger for the nodes at high wavemodes (small scales) [1].

Cosmology can also constrain the absolute scale of neutrino masses. The main effect of increasing the sum of the neutrino masses is to obtain a change in the early and late ISW effects, if the other cosmological parameters are changed to fix the angular position of the CMB peaks. Since the freedom in the PPS can compensate the changes in the early and late ISW effects without altering the other scales, the marginalized constraints on  $\Sigma m_\nu$  are weakened in the PCHIP PPS case, as it is possible to see in Fig. 2.

The inclusion of the CMB polarization at high multipoles by Planck, however, prevents the compensation between PPS parameters and neutrino properties, and

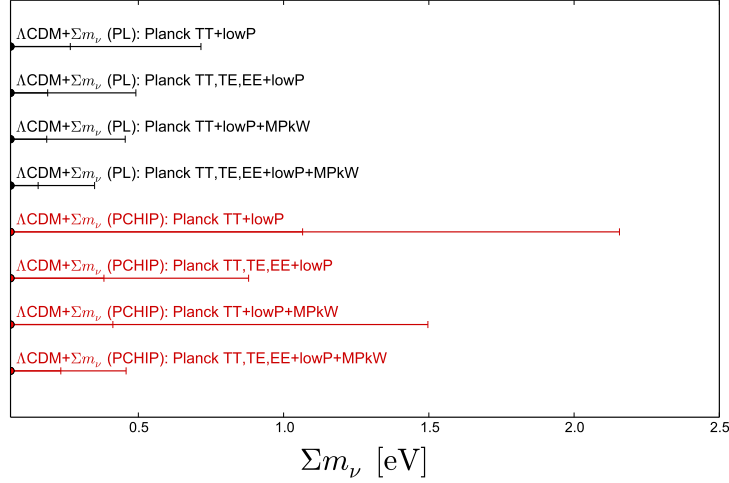


Figure 2: Limits on  $\Sigma m_\nu$  at 1, 2  $\sigma$ . Adapted from Ref. [1].

$\Sigma m_\nu$  and  $N_{\text{eff}}$  are forced to be very close to the standard values  $\Sigma m_\nu \simeq 0.06$  eV and  $N_{\text{eff}} = 3.046$ , also with a free PPS. This happens because the effect of a free PPS on the TT, TE and EE spectra is different from the effects of increasing  $\Sigma m_\nu$  or  $N_{\text{eff}}$ .

## 4 PPS Results

An helpful way to visualize how the free PPS is constrained by data in our model is to plot the marginalized constraints on the PPS shape, as in Fig. 3. These are obtained marginalizing over the obtained PPS for each different value of  $k$  independently.

The reconstructed PPS has several interesting properties. First of all, the least constrained nodes are in  $k = 5 \cdot 10^{-6} \text{ Mpc}^{-1}$  and  $k = 10 \text{ Mpc}^{-1}$ , as expected due to the absence of data at these wavemodes. The nodes from  $k \simeq 0.007 \text{ Mpc}^{-1}$  to  $k \simeq 0.2 \text{ Mpc}^{-1}$ , instead, are the best constrained. In this region the PCHIP PPS is in perfect agreement with the power-law PPS. Two features appear at small wavemodes: there are a small dip ( $\simeq 2\sigma$ ) at  $k \simeq 0.002 \text{ Mpc}^{-1}$ , corresponding to the dip at  $\ell \simeq 25$  in the CMB temperature spectrum, and a small bump ( $\simeq 1\sigma$ ) at  $k \simeq 0.0035 \text{ Mpc}^{-1}$ , corresponding to the small bump at  $\ell \simeq 40$  in the CMB spectrum.

## 5 Conclusions

We noticed the presence of possible degeneracies between the PPS of scalar perturbations and the parameters that describe the dark radiation properties. As a con-

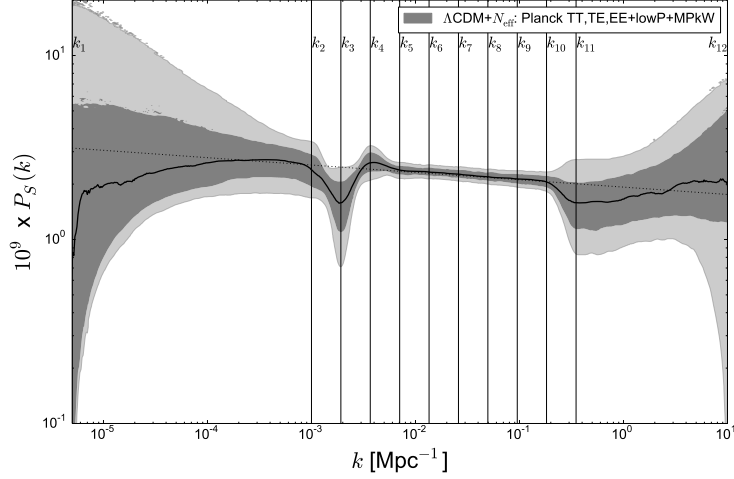


Figure 3: 1, 2  $\sigma$  bounds on the constrained PPS compared with the best-fit PL PPS. From Ref. [1].

sequence, the limits on the effective number of relativistic particles  $N_{\text{eff}}$  and on the total neutrino mass  $\Sigma m_\nu$  from the CMB temperature data are relaxed. The CMB polarization, however, helps to break the degeneracies between the dark radiation parameters and those related to the PPS of scalar perturbations.

The analyses show that possible features in the PPS exist, in particular at large scales. These may suggest that some new mechanism for inflation must be present, in order to introduce a scale dependency in the initial power spectrum of scalar perturbations, as it is observed in the CMB spectrum.

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